Resonant Enhanced Modulator Development

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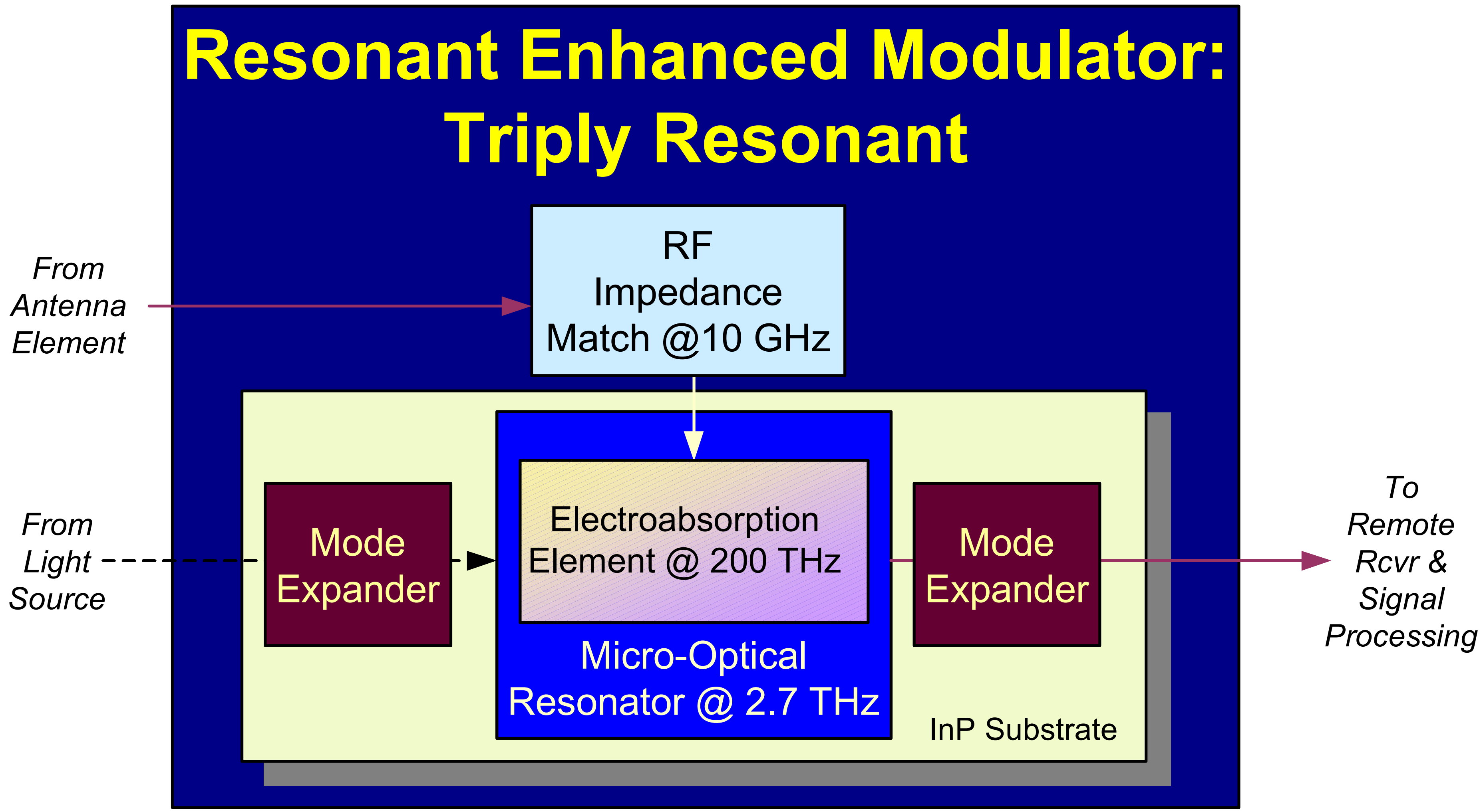
August 1, 2001

Principle of Operation



Resonant Enhanced Modulators

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Electrical and Computer Engineering
University of Illinois at Urbana-Champaign
Advanced Processing and Circuits Group

Radio-Frequency Lightwave Integrated Circuits
DARPA/MTO

Objectives

- Objective: A Low V_π Modulator (< 100 mV)
- Approach: Laterally Coupled InP Based Microring Resonators
- Program Started 6/13/00; to End 6/13/03
- Milestones
  24 mos … Prototype REM
  30 mos … Optimized REM
  36 mos … 12 Deployable REMs

First Year Accomplishments

10/20/00
- Demonstrated Smooth Anisotropic ICP Etching
- Analyzed Loss Requirements for Microrings
- Designed Delay Line Microwave Circuit

2/16/01
- Fabricated Test Structures
- Began Characterizing Test Structures
- Engineering Design Begun

7/30/01
- Achieved High Quality Nanofabrication Process
- Demonstrated InP resonators with Q=20,000
- Demonstrated 2 cm^{-1} waveguide losses

Milestones Coming Year

- Fabricate Prototype Structure (4/01) late
- Characterize Modulated Ring Properties (6/13) late
- Developmental REM device (12/01)

Tech Transition

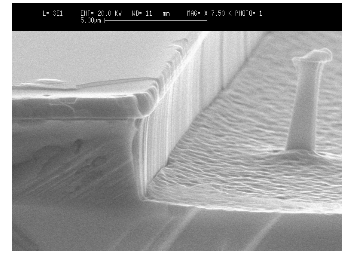
- Supply Deployable REMs to System Organization
- Production by Sarnoff

REM Fabrication Activities

Fabrication:

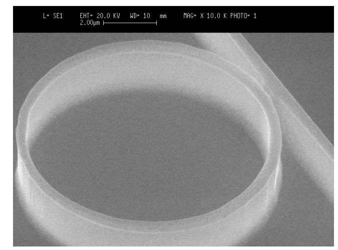
June, 2000 — **Program Start**

- ICP Characterization
- Leica/Cambridge e-beam initial use



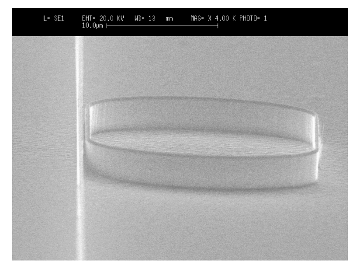
October, 2000 — **Ring nanostructures reported by UIUC**

- Resist development
- Etching condition studies
- Leica/Cambridge e-beam dosage studies
- Etching of coupling region

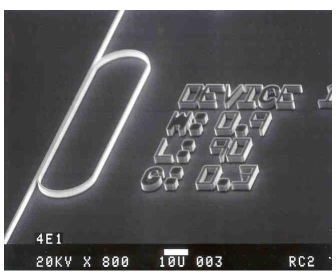


February, 2000 — **Sample microrings delivered to Sarnoff**

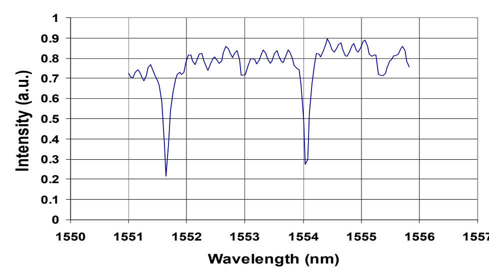
- Resist quality development (cont'd)
- Pattern interchange (Sarnoff-UIUC)
- Sample handling
- Stitching issues



May, 2000 — **Routine characterization of microrings structures at Sarnoff**



- Resist development (cont'd)
- Switch to new JEOL e-beam tool
- Switch to larger rings for diagnostics



Sarnoff Meso-Optics Programs

Lateral Ring Technology (LRT) Approach

- DARPA RFLICs *Resonant Enhanced Modulator* Program

Vertical Ring Technology (VRT) Approach

- NRO *Low V_π Modulator* Program
- Princeton Lightwave, Inc. *Vertical Ring Technology* Program

Princeton Lightwave, Inc., a spin-off company from Sarnoff Corp, has begun to pursue interests in meso-optics at Sarnoff (Nov, 2000).

Two PLI staff members participate in the PLI program at Sarnoff:

G. Griffel
S. Park

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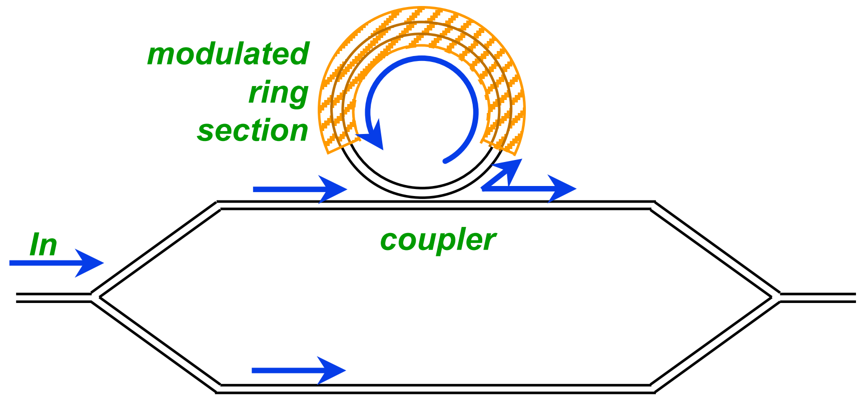
Ring Resonator M-Z Modulators

Radio-Frequency Lightwave Integrated Circuits DARPA/MTO

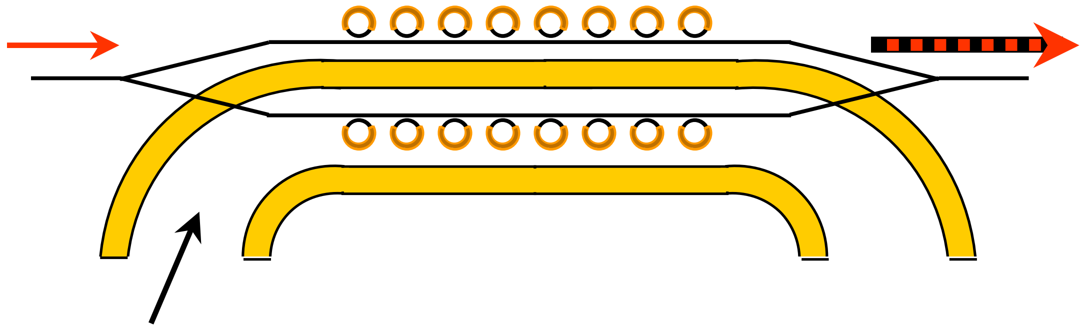
- **Phase modulation due to coupled resonators**
- **Combine multiple resonators to achieve performance enhancement**

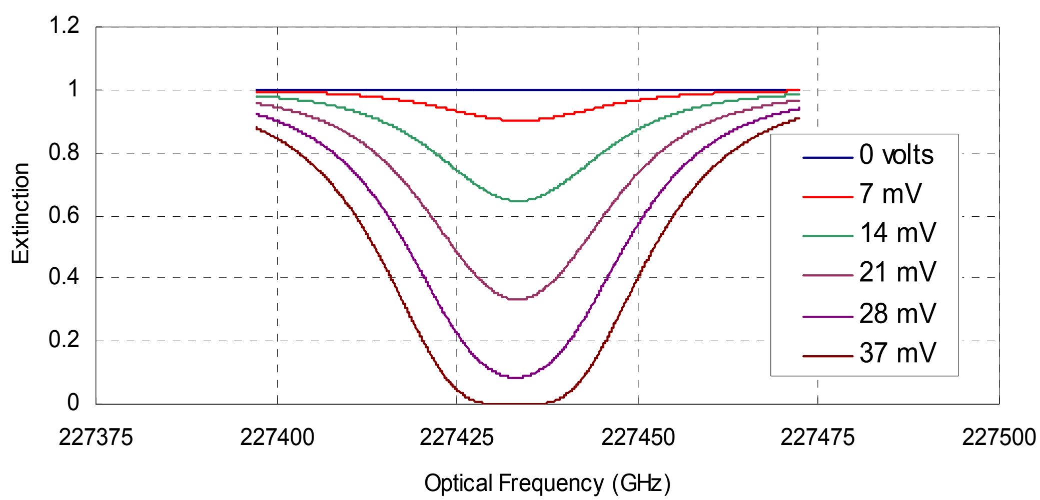


		Passband (GHz)			Photon Lifetime (psec)		
diameter	FSR	Finesse=	Finesse=	Finesse=	Finesse=	Finesse=	Finesse=
(um)	(GHz)	3	10	30	3	10	30
5	5968	1989	597	199	0.1	0.3	0.8
10	2984	995	298	99	0.2	0.5	1.6
20	1492	497	149	50	0.3	1.1	3.2
50	597	199	60	20	0.8	2.7	8.0
100	298	99	30	10	1.6	5.3	16.0

Reported today

Allows for V_π < 100 mV Modulation



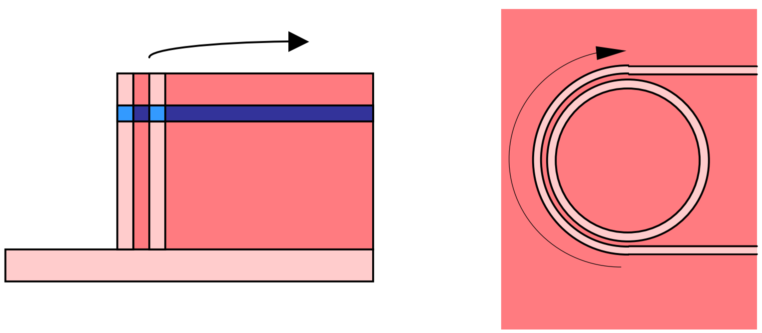


- **Push-Pull Configuration**
- **37 mV = V_π**
- **10 GHz Operation**
- **Requires loss of ~1 cm^{-1}**
- **Optically narrowband**

Lateral Ring Technology (LRT)

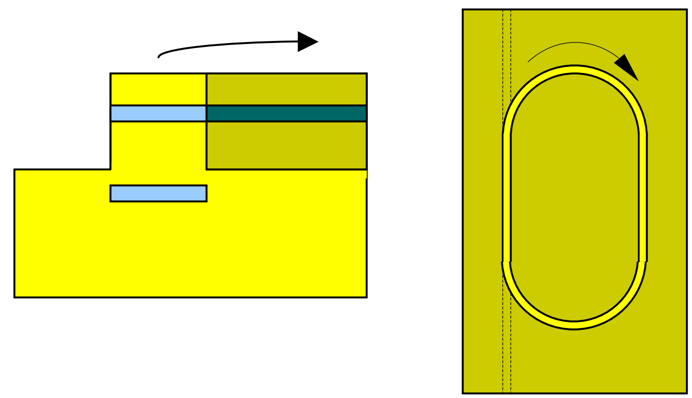
… compare to Vertical Ring Technology (VRT) …

- **Lateral Ring Technology**
  - \+ Few lithography steps
  - \+ Coupling strength high
  - \+ High-index-contrast submicron waveguides



  - – Submicron lithography
  - – Uniformity requirements

- **Vertical Ring Technology**
  - – Complex fabrication
  - – Coupling too weak, except with:
    - » High bend losses (or submicron rings)
    - » High waveguide transition losses
    - » High-index-contrast lower guides



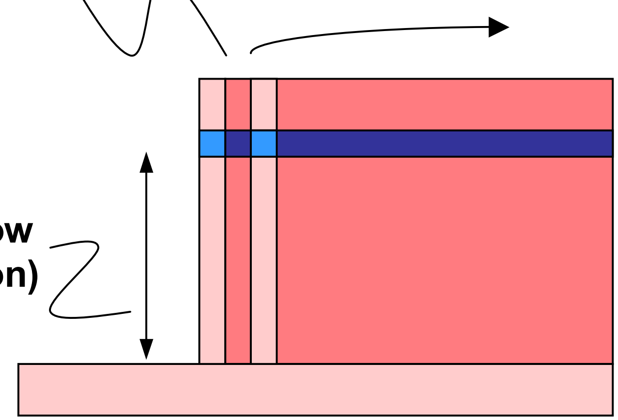
  - \+ Coupling mediated by epitaxy
  - \+ Active/passive integration easy
  - \+ Optical lithography

Prefer <u>LRT</u> for RF applications (<40 μm dia. rings)

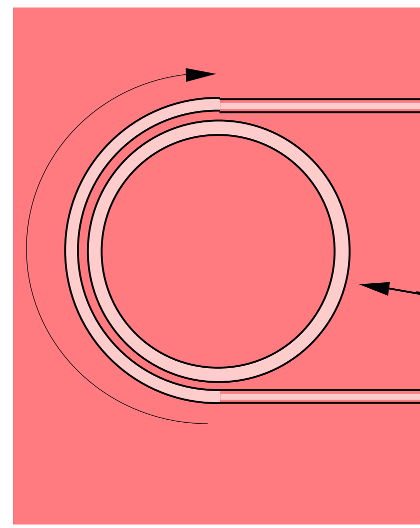
Features of Lateral Ring Technology

Coupling between 2 identical guides

Deep etch (~2 μm below active region)



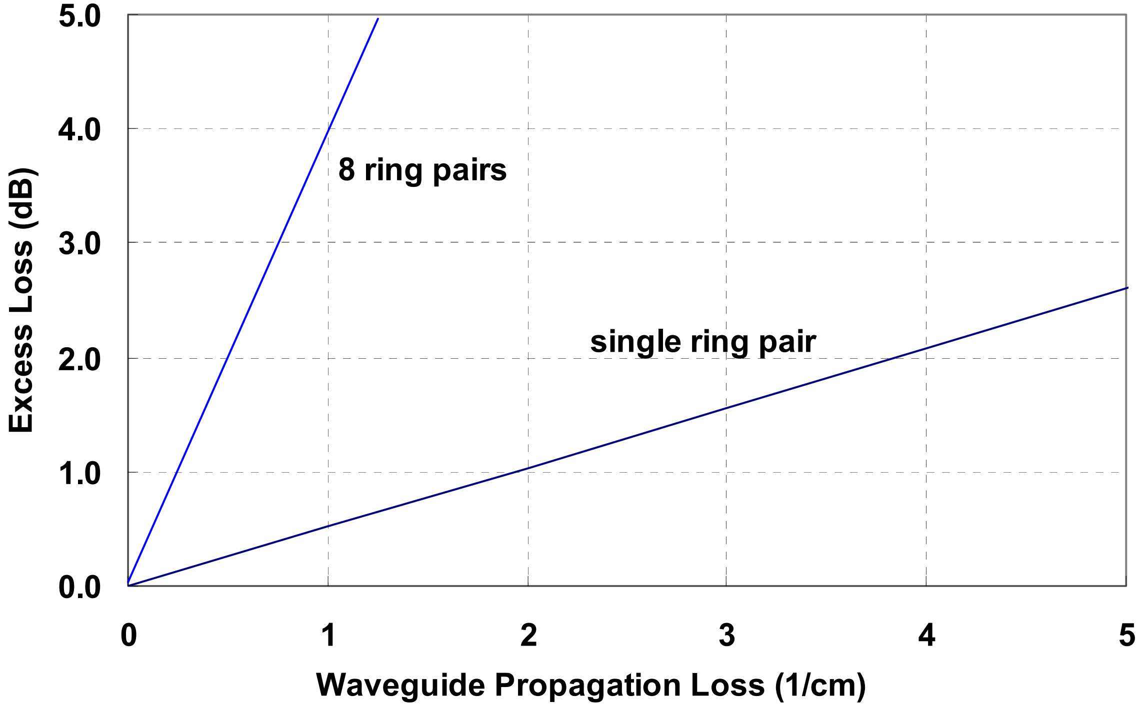
Resonator radius of curvature: constant



Small diameter (under 40 μm)

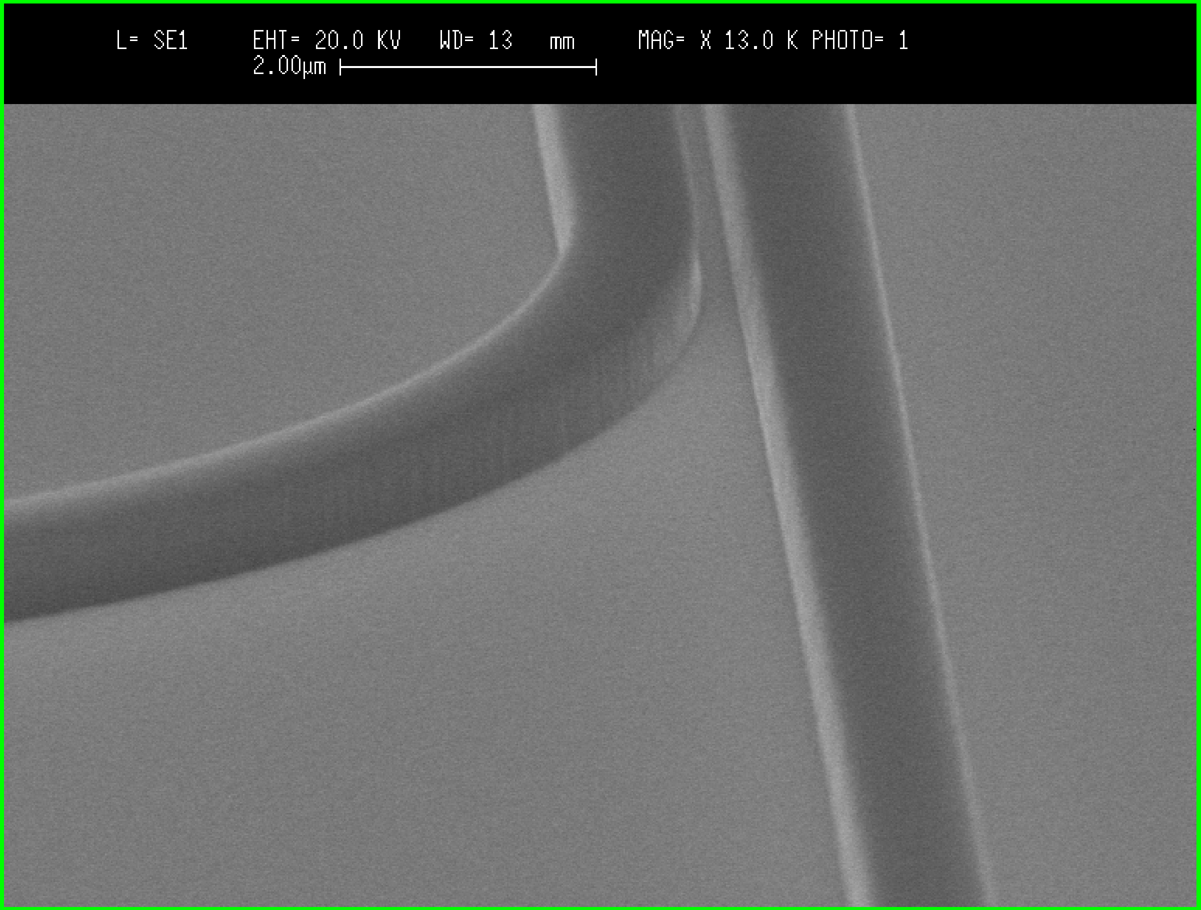
Coupling strength difficult to achieve; at a premium for smaller structures; wrap-around structure can help

Challenges to Implementation of Meso-Optics



- **Highly confined waveguides**
- **Low roughness, high-aspect-ratio waveguide fabrication**
- **High-strength, low-excess-loss couplers**

SiO2 Etch Mask Developed at UIUC



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Etching Regimes

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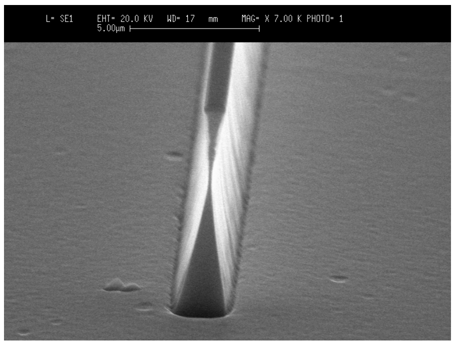
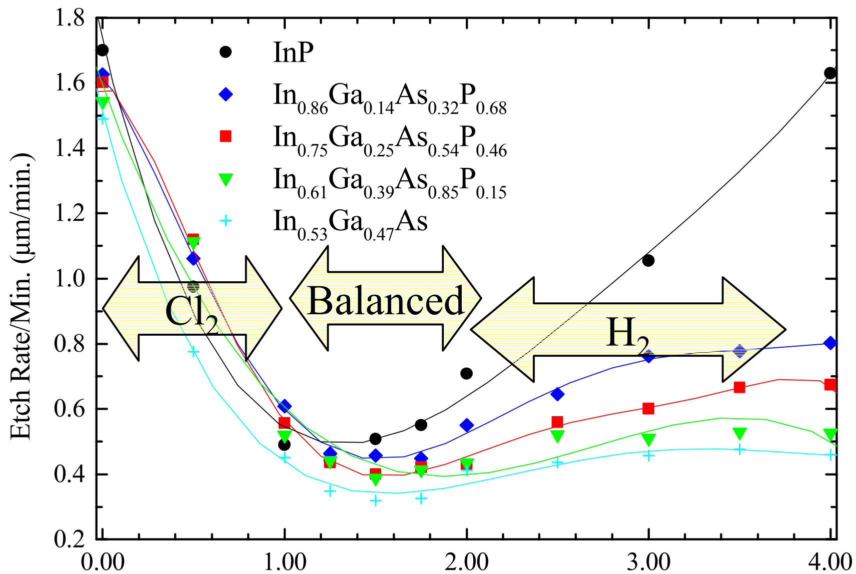
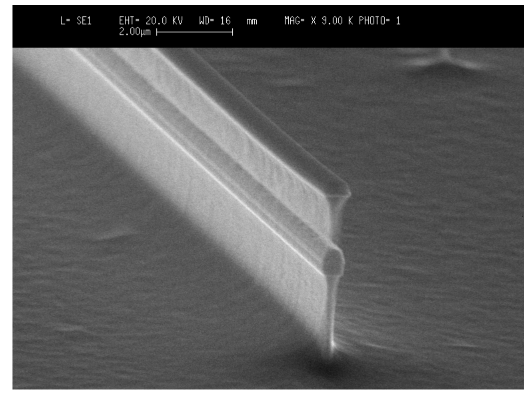
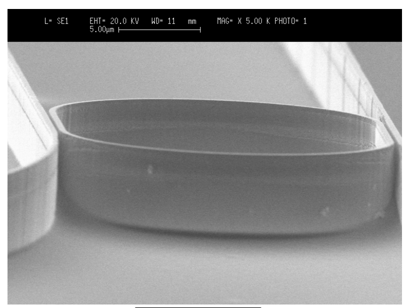


Cl_2



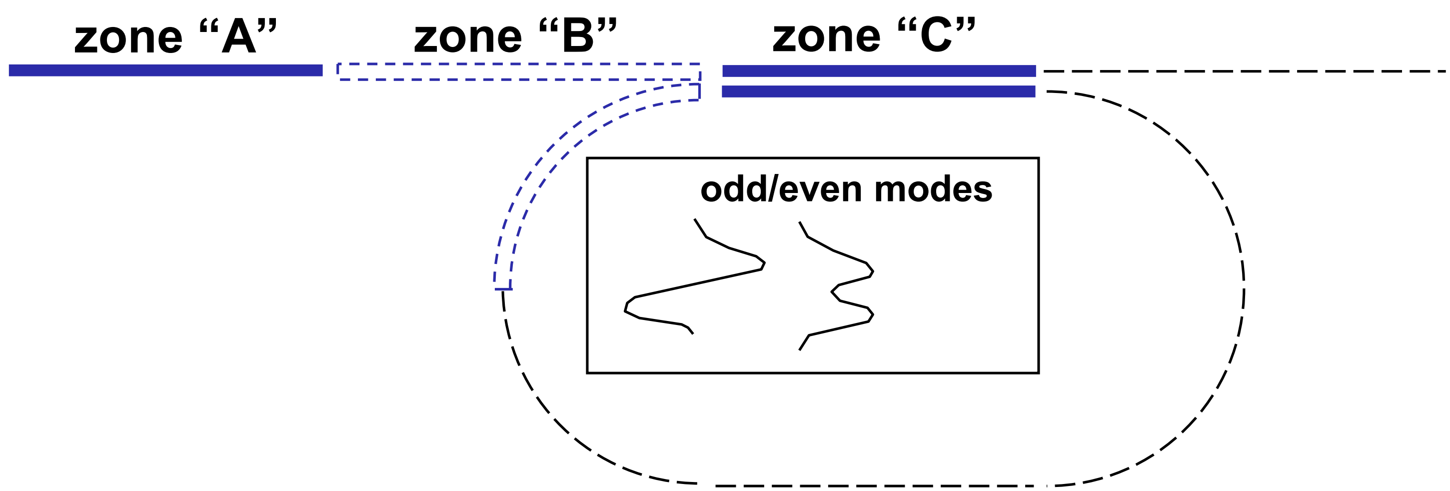


H_2



Balanced

Coupling Loss is a Key Issue



zone "A" -- Well-understood, low loss attainable; depends on material and roughness

zone "B" -- Poorly understood; low loss believed to require strongly localized "bound array modes" in zones "B" and "C." (Data suggest issues in zone "B.")

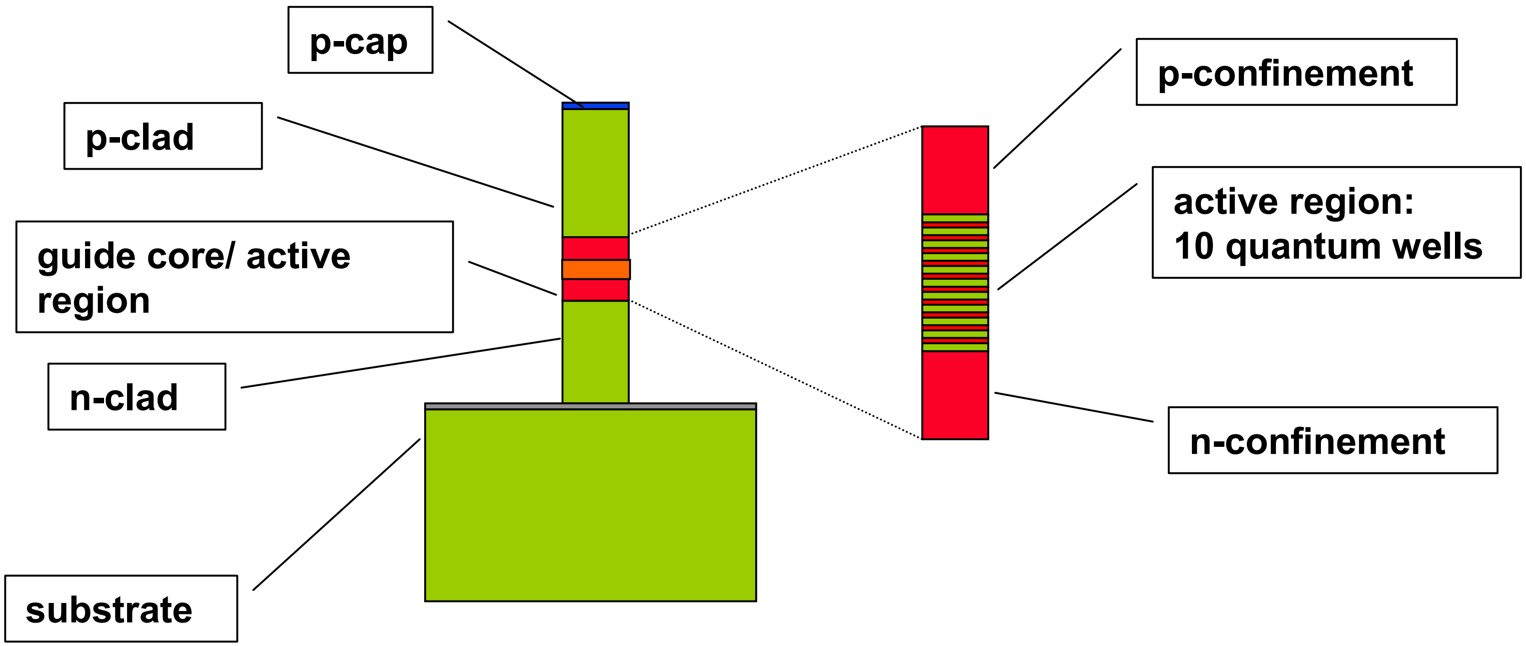
Excessive overlap with radiation modes causes loss

zone "C" -- Well understood, low loss attainable; (see zone "A" criteria)

Laterally Coupled InP-based Ring Parameters

Guide width:	0.8 to 1.0 μm	Structure Parameters
Circumference:	200 to 400 μm	
Free Spectral Range:	1.6 to 3.4 nm	
Coupler length:	50 to 150 μm	
Coupling gap:	0.3 to 0.45 μm	
FWHM:	0.09 to 0.73 nm	Optical Parameters
Finesse:	4.7 to 28	
Q:	2,000 to 17,000	
RT Loss:	0.8 to 4.4 dB	
Coupling:	3% to 36%	

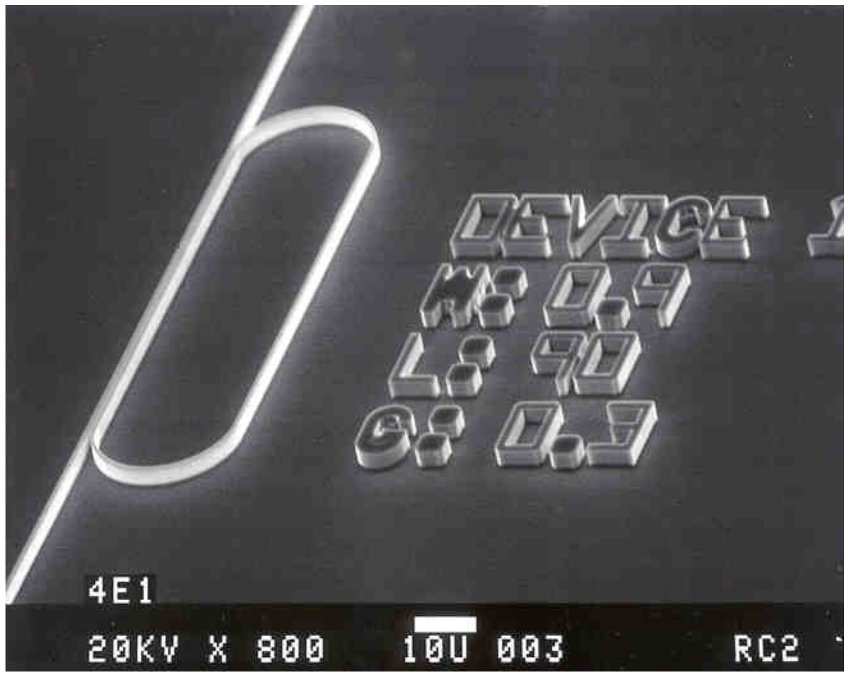
Structure of Waveguide and Active Region



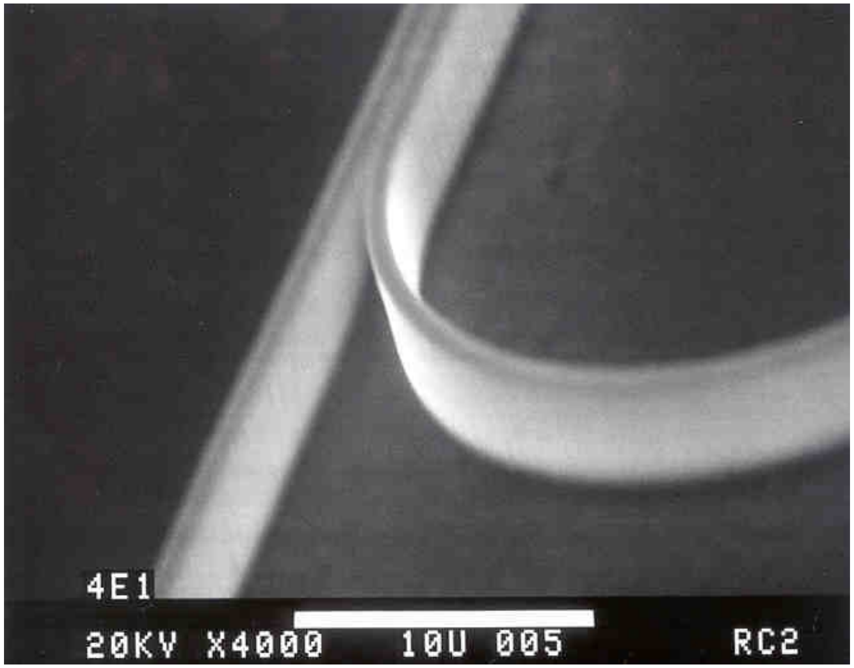
Critical design goals:

- Low bending loss
- Single mode operation
- Strong electro-optic effect

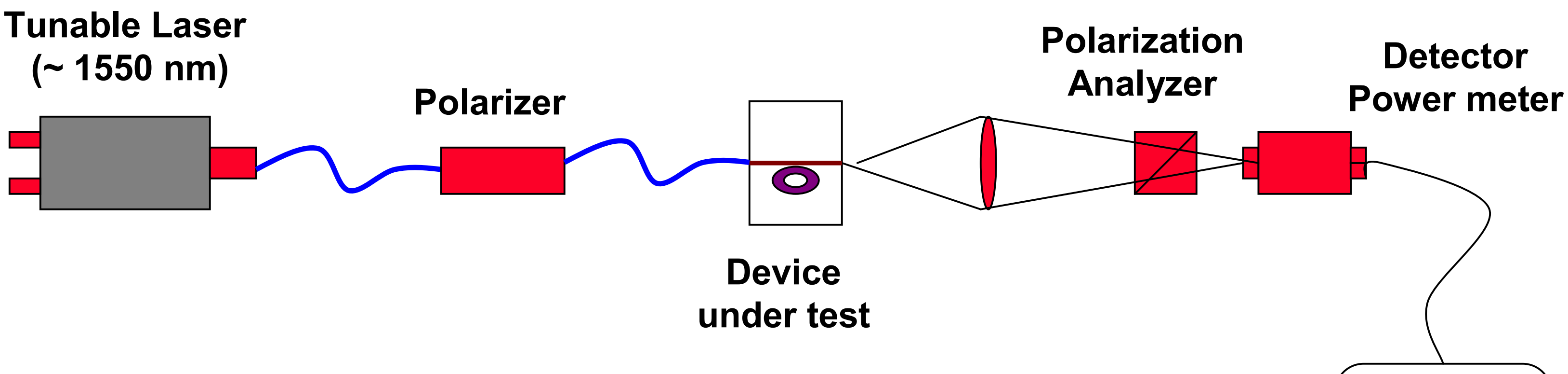
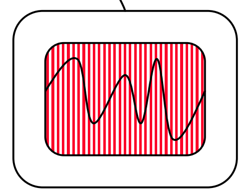
Deeply Etched InP Ring Resontator

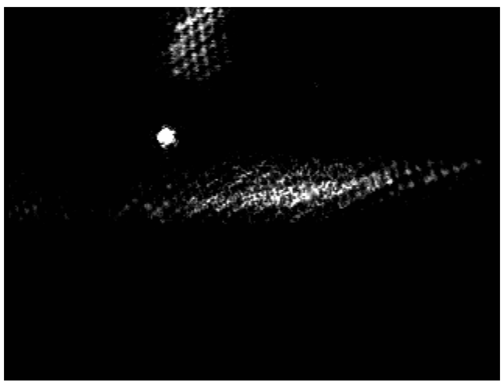


Ring Resonator Detail



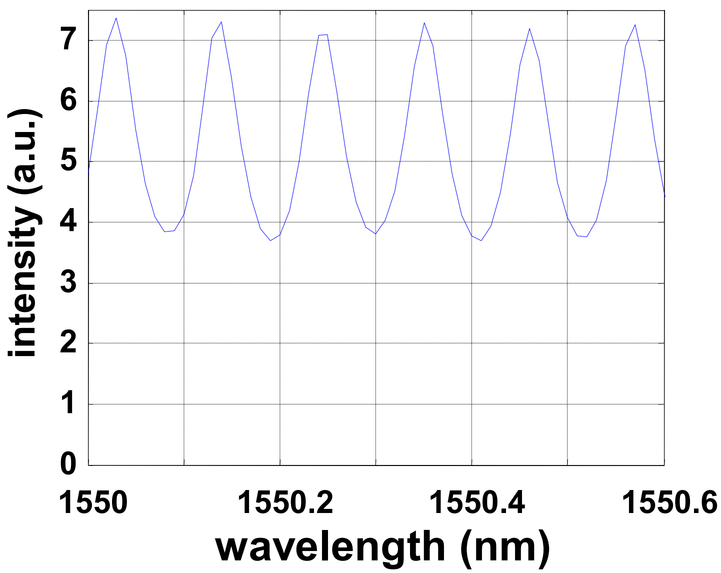
Experimental Setup

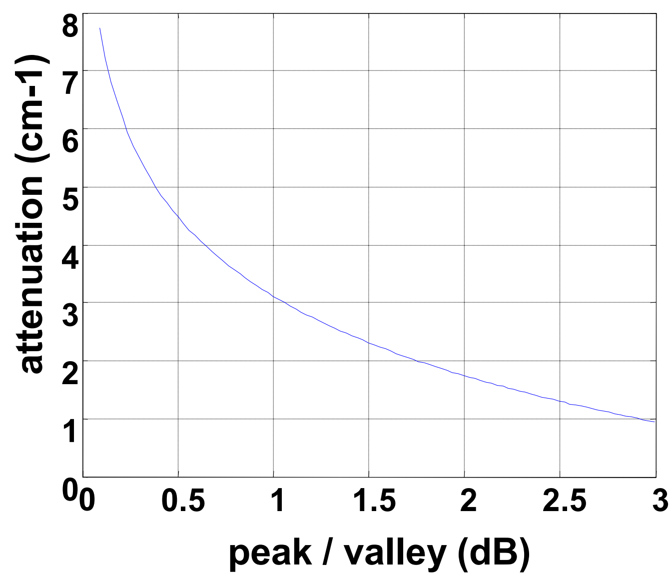





Determining Loss in Linear Waveguides

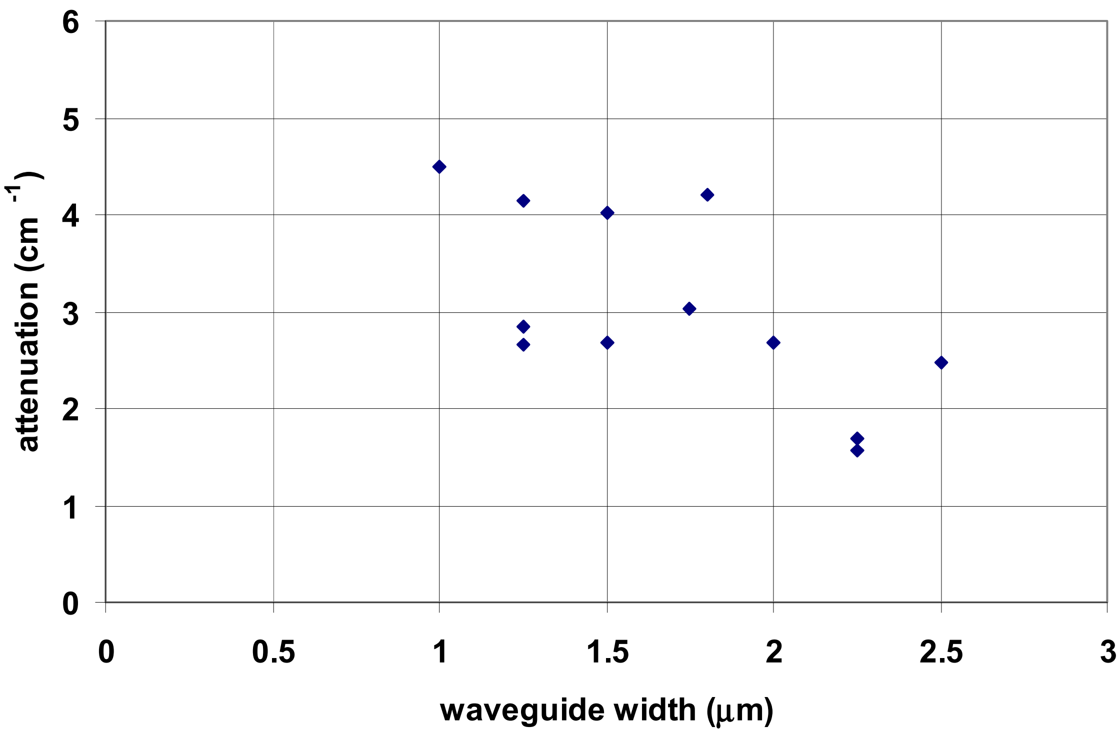
Fabry-Perot Resonator Formed by Cleaved Facets





The peak to valley ratio measures the attenuation

Attenuation vs Waveguide Width in Straight Guides



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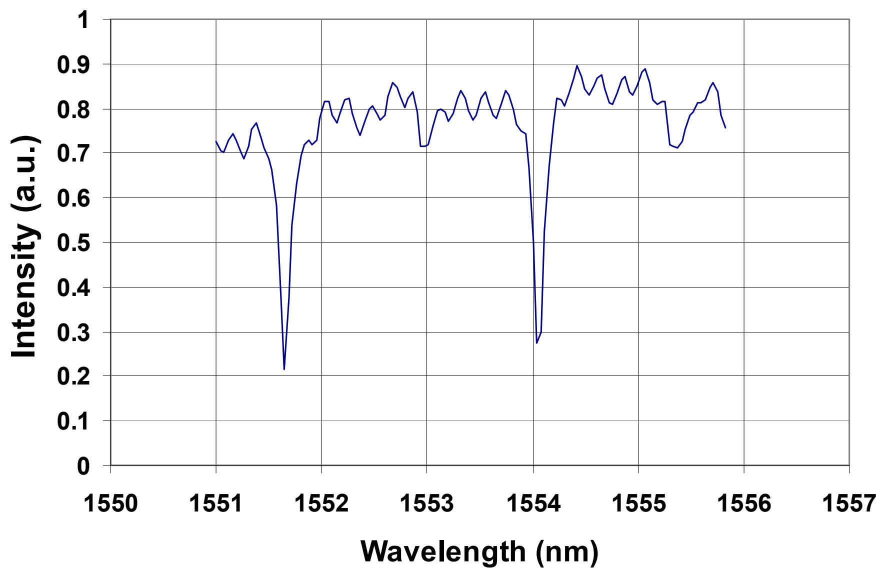
Attenuation in Deeply Etched Linear Waveguides

	GaAs Based		InP Based	
Depth (mm)	2.0	2.5		3.0 – 4.0
Width (mm)	0.42 - 0.62	0.4	1.8	1.0 – 2.5
Etch	CAIBE (Ar, Cl_2)	ICP	RIE (CH_4, H_2)	ICP
Loss (cm-1)	2.5	5.0	~1.0	1.5 – 4.5
Reference	U.Md. (P.T. Ho) PTL 3/2000	Northwestern (S.T. Ho) PTL 12/1999	HHI (Rabus & Hamacher) PTL 8/2001	Sarnoff (J.H. Abeles) 7/2001

Resonance



Quantum Well Structure:

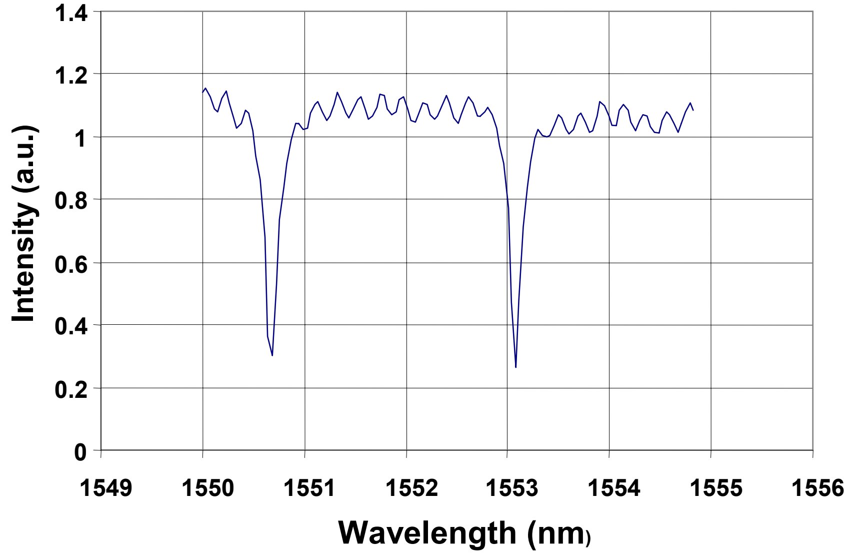
•10 QWs (InGaAsP/InP)

• λ_g: 1400 nm

•Active Layer Thickness: 0.5 μm

Waveguide width:	1.0 μm
Racetrack circumference:	274 μm
Coupling length:	90 μm
FSR:	2.41 nm
Finesse:	21
Q:	13,500
Effective Ring Attenuation:	8.6 cm^{-1}
Coupling:	6.41%

Resonance



Quantum Well Structure:

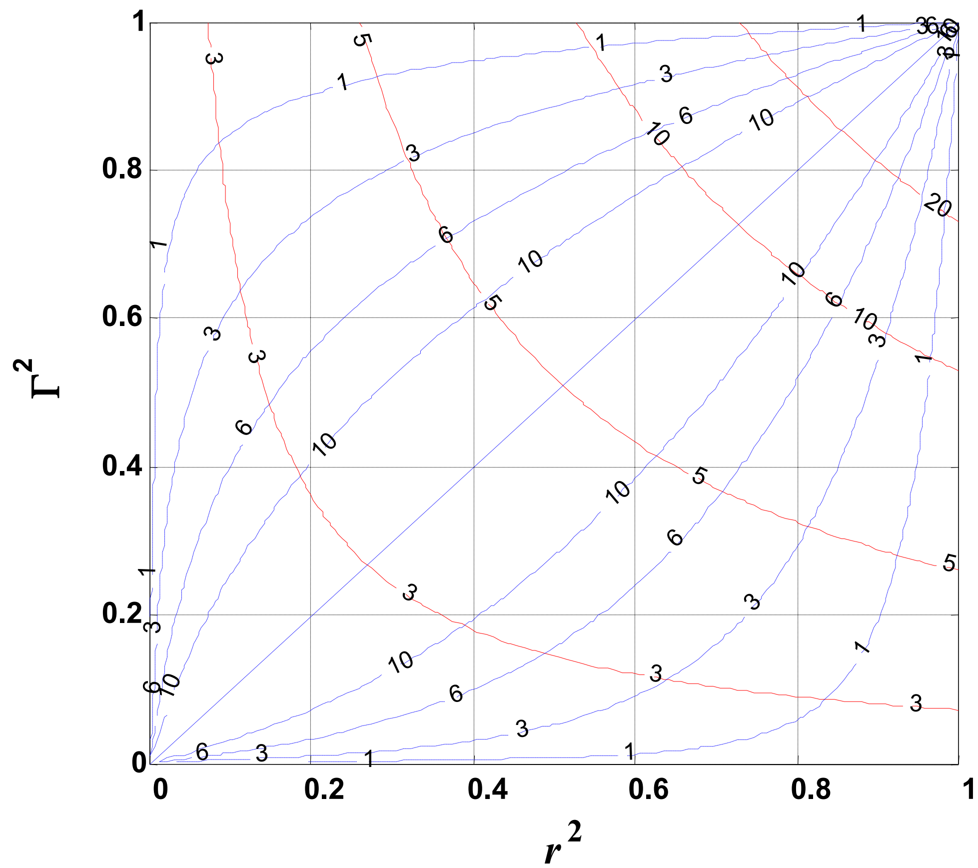
•10 QWs (InGaAsP/InP)

• λ_g: 1400 nm

•Active Layer Thickness: 0.5 µm

Waveguide width:	0.9 µm
Racetrack circumference:	274 µm
Coupling length:	90 µm
FSR:	2.41 nm
Finesse:	13
Q:	8,400
Effective Ring Attenuation:	13 cm^{-1}
Coupling:	11%

Finesse and Peak-to-Valley Ratio



$$\Gamma^2 = e^{-\alpha L}$$

$$r^2 = 1 - \kappa^2$$

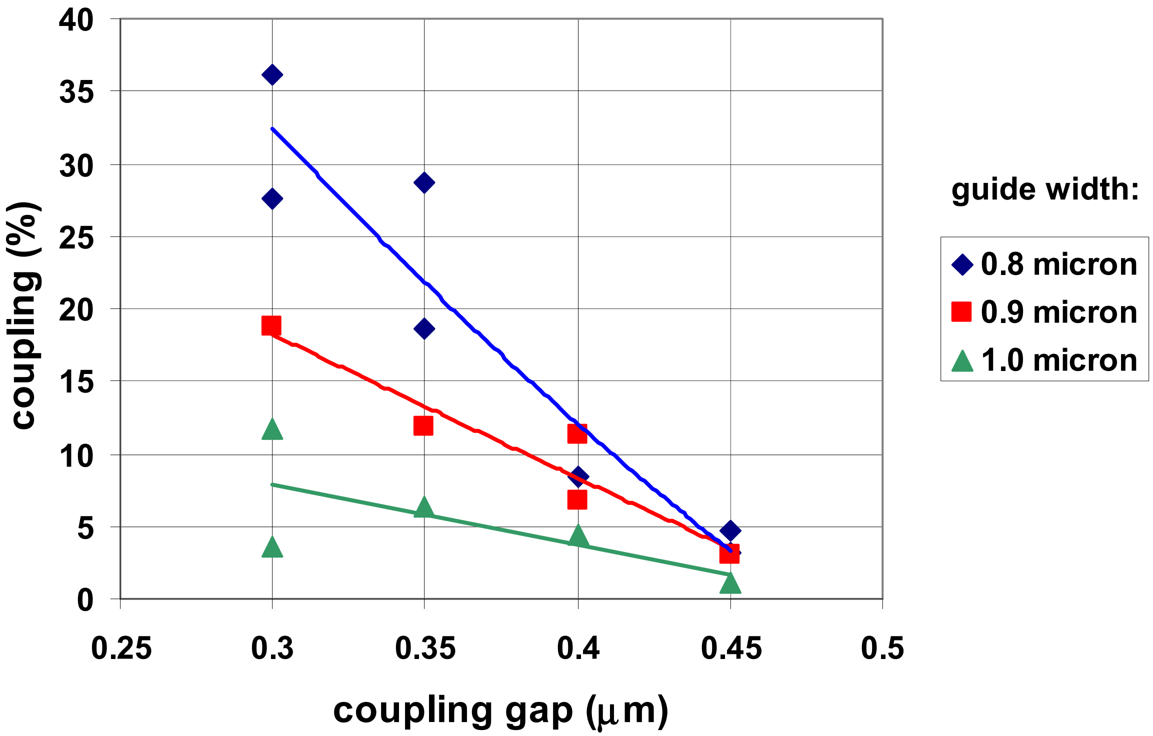
(κ^2 = power coupling)

Finesse

Peak / Valley (dB)

A measurement of (Finesse, Peak / Valley) determines (Γ, r)

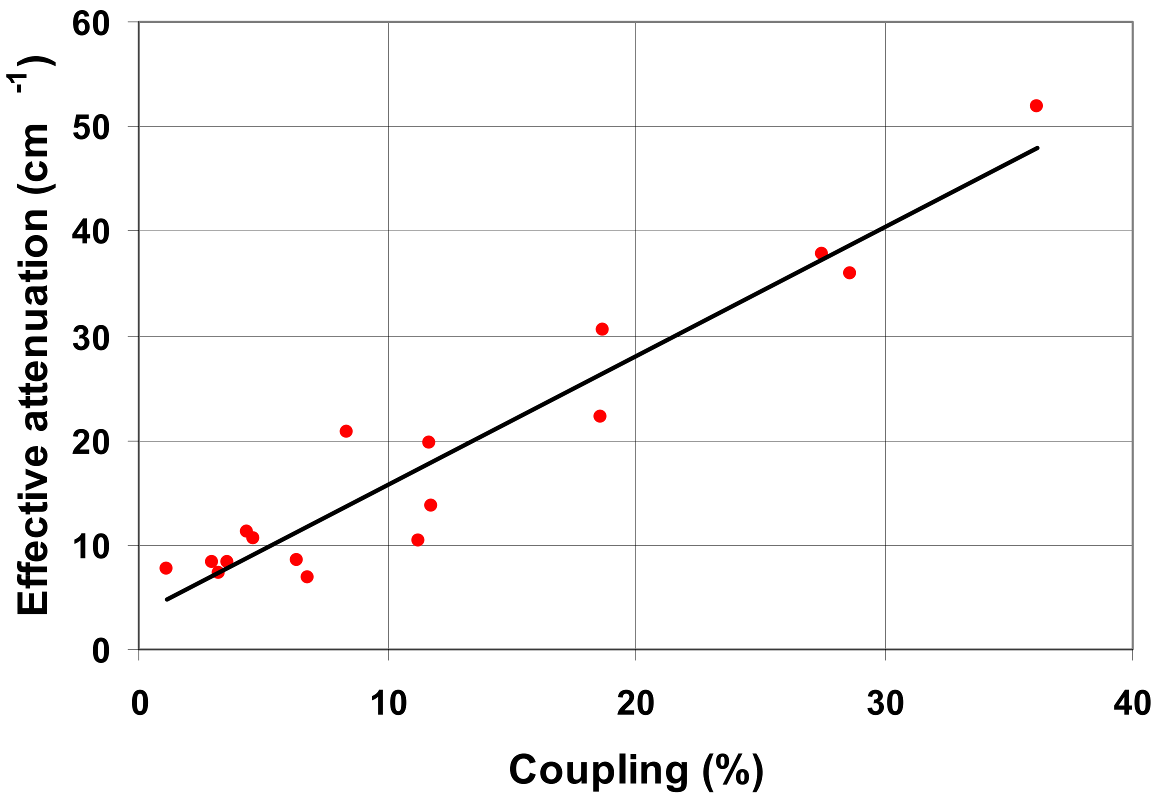
Coupling vs Gap Width



Effective Loss Depends on Coupling

Effective attenuation = (1/*L*)ln(*t*), inferred from resonator characteristics

(where *L* is circumference and *t* is the transmission per round trip)



Zone "B" is contributing significant loss

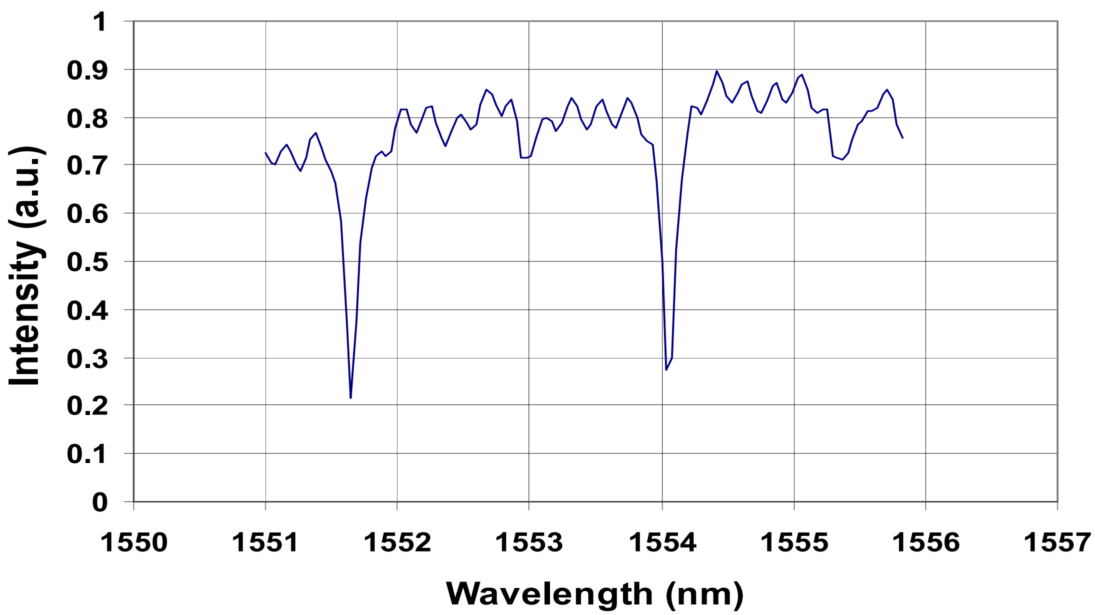
Requirements for REM

- Photon lifetime must be τ_p < 3 psec for 10 GHz
  $\{\tau_p = 1/\omega = 1/(2\pi f)\}$
- Photon lifetime must be ~10x the single round trip time
  {for 10x photon recycling enhancement}
- Therefore single round trip must last <0.3 psec
- Therefore, circumference must be L < 30 μm

need to reduce length and reduce coupling
while maintaining low coupling loss

32x Photon Lifetime Enhancement

… from data …



- **Observed *Q* of 17,000 in a resonator of circumference 265 μm**
  - **Implies photon lifetime of 85 psec**
  - **Roundtrip time of 2.6 psec**

- **Photon lifetime enhancement = 32x**

Summary

- **Nanofabrication has been demonstrated**
  - **-- Remains to become a highly reproducible process**
  - **-- Sufficient for this program**

- **Microresonator characteristics are encouraging**
  - **-- Excellent photon lifetime enhancement (x32)**
  - **-- Exceeds requirements for the REM**

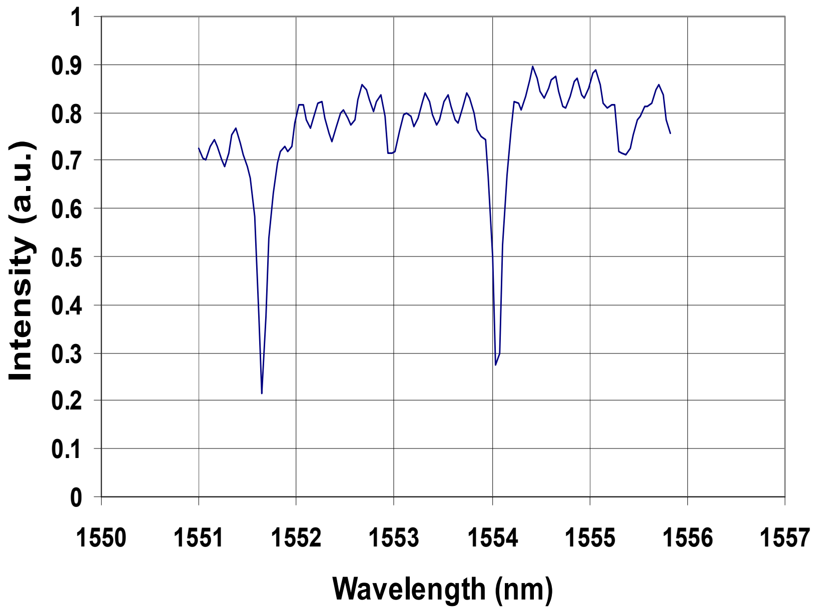
- **Microresonator characteristics still require refinement**
  - **-- Need reduction in circumference (~10x)**
  - **-- Large coupling observed with larger rings bodes well for adequate coupling with smaller rings**

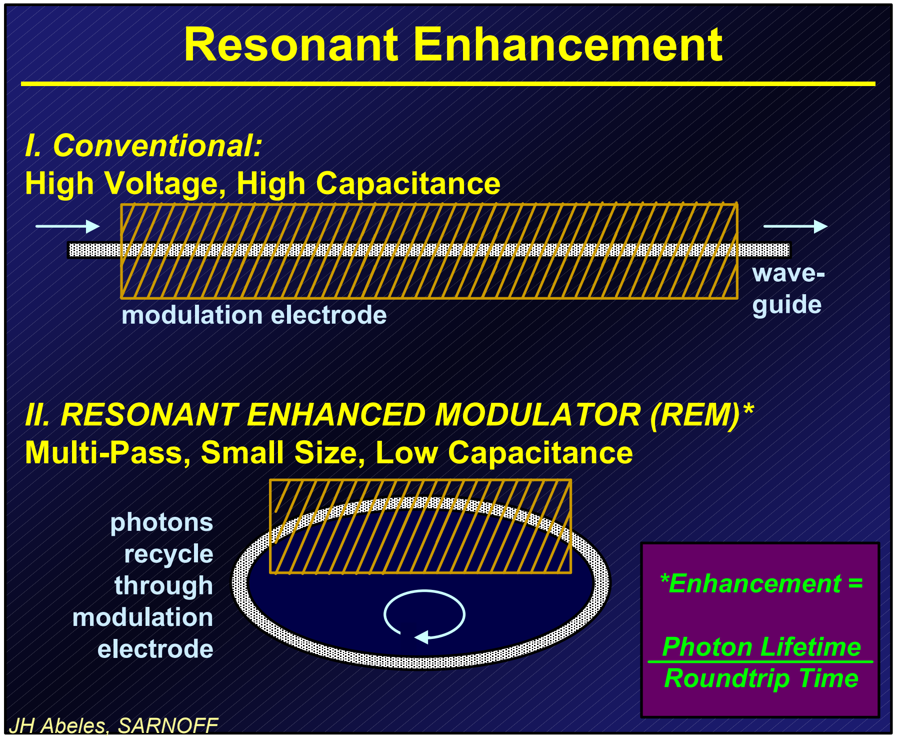
- **Continue to fabricate rings and zero-in on the smaller sizes**

- **Go ahead and make prototypes with larger rings (which function at lower frequencies), e.g., a 2 mV, 1 GHz modulator.**

Most Significant Accomplishment

- **Achievement of 32x photon recycling enhancement in a InGaAsP based microring resonator**





- **Photons travel around the ring 32x on average!**

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Program Roadmap

- Year 2
  - Obtain electrorefractive ring modulator (24 months)
  - Demonstrate electrorefractive ring modulator REM (24 months)

- Year 3
  - Demonstrate 10 GHz electrorefractive ring modulator
  - Demonstrate 100 millivolt class V_{π} modulator (30 months)
  - Deliver 12 REM devices to DARPA (36 months